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## FINAL REPORT

Photoreflectance for the In-situ Study and Characterization of Semiconductor Growth  
and Processing

DAAL 03-92-G-0189

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## ABSTRACT

The objective of this program was to utilize photoreflectance for the *in-situ* and *ex-situ* study of a number of fundamental as well as applied properties of semiconductors, semiconductor microstructures, semiconductor surfaces/interfaces as well as actual device structures. These include (a) the determination of the substrate temperatures and alloy composition during actual growth at elevated temperatures, (b) a detailed *in-situ* study of Fermi level pinning, passivation, and Schottky barrier formation as well as other surface state studies on a number of semiconductors, (c) characterization of actual devices structures such as heterjunction bipolar transistors and high electron mobility transistors, (d) interfacial strain at the Si/SiO<sub>2</sub> interface, (e) InGaAs/AlGaAs and GaSb/GaAlSb quantum wells, multiple quantum wells, and superlattices, and (f) the electron-phonon interaction in reduced dimensional systems.

## RESULTS

### I. *In-situ* Studies of Fermi Level Pinning on GaAs(001) Surfaces

- A. We have performed a contactless electromodulation [photoreflectance (PR) and contactless electroreflectance (CER)] study of undoped/ $p^+$  GaAs (001) surfaces (so-called *UP* structures) fabricated by MBE, which exhibit reduced surface state densities and surface Fermi level pinning values closer to the band edge in relation to other  $p$ -or  $n$ -type GaAs (001) surfaces. The temperature dependence of the measured barrier height has been explained by a modified current-transport equation which contains two "pinning" levels (0.25 V and 0.5 V, relative to the valence band). Measurements were carried out in air (CER) and in-situ (PR) in the ultrahigh vacuum environment of the MBE chamber soon after growth and before the sample was removed to air.
- B. We have conducted an *in-situ* study of the Fermi-level pinning behavior of  $n$ - and  $p$ -type GaAs (001) surface in the ultrahigh vacuum environment of a molecular-beam-epitaxy chamber using photoreflectance. The surface electric fields were determined from the Franz-Keldysh oscillations observed on *UN* and *UP* samples. As-grown surfaces as well as the effects of a few monolayers of arsenic deposition/desorption were investigated. The measured barrier heights of the as-grown  $n(V_{B,n})$ - and  $p(V_{B,p})$ -type samples (relative to their respective band edges) were 0.61 V (midgap pinning taking into account the photovoltaic effect) and 0.33 V, respectively. The *in-situ* deposition of a few monolayers of arsenic had no effect on  $V_{B,n}$  but caused  $V_{B,p}$  to increase to 0.6 V, i.e., midgap pinning. The desorption of the arsenic layers brought  $V_{B,p}$  close to its as-grown value but had no effect on  $V_{B,n}$ . The results are summarized in Fig. 1. These observations, together with earlier studies on similar but air-stabilized samples, provides evidence that arsenic plays a crucial role in the formation of the surface Fermi levels in GaAs.

### II. Device Structures

- A. We have performed a study of the PR spectra from a GaAs/GaAlAs heterojunction bipolar transistor (HBT) structure as a function of the intensity of both the probe and pump beams. Our results show that there is a significant photovoltaic contribution to the PR signals. We have presented new results on the illumination dependence of the fields from both the collector/base ( $F^{coll}$ ) and emitter/base ( $F^{emitt}$ ) regions obtained from the Franz-Keldysh oscillations (FKOs) in the PR spectra from the relevant regions. This experiment has demonstrated that (a)

doping levels in the collector and emitter regions can be obtained from the illumination dependence of the observed fields while (b) the fields themselves can be used to evaluate variations in doping levels.

Shown in Fig. 2 is the PR spectrum at room temperature from a GaAs (collector)/GaAlAs (emitter) HBT. The spectral features beginning at about 1.4 eV and 1.8 eV are FKOs originating in the collector/base and emitter/base fields, respectively. Figures 3 and 4 show the calculated field profile in the collector/base and emitter/base regions, respectively, in the dark (solid lines) and under illumination (dashed lines).

- B. Using the chopping frequency dependence of the PR signals from the collector/base and emitter/base regions of a GaAs/GaAlAs HBT (see Fig. 2) we have performed a contactless determination of the time constants of both the GaAs collector and GaAlAs emitter portions of the device. The modulation frequency was in the range of  $2 \text{ Hz} < f_m < 100 \text{ kHz}$ . Both in-phase and quadrature signals from both these regions were recorded. An analysis of the collector/base time constant revealed that the recombination mechanism at this interface is dominated by the hole current and is due to midgap states. The experiment demonstrated a new area of application for PR as a characterization method for these devices.

Displayed in Figs. 5 and 6 are the in-phase (open circles)/quadrature (closed circles) signals as a function of  $f_m$  for the GaAs collector and GaAlAs emitter signals, respectively. The solid/dashed lines are fits to a Lorentzian type function making it possible to evaluate the respective time constants.

### III. Temperature Dependence of the Broadening Parameter of Low-dimensional Systems.

- A. From a detailed line-shape fit to the piezoreflectance spectra, we have evaluated the temperature dependence ( $19\text{K} < T < 420\text{K}$ ) of the energies  $[E(T)]$  and broadening parameters  $[\Gamma(T)]$  of the fundamental transitions in bulk Ge and two narrow Ge/GeSi multiple quantum well structures. The experimental broadening parameters were compared with theoretical expressions.  $\Gamma(T)$  can be used to evaluate the electron-phonon interaction. No significant dimensionality dependence of  $\Gamma(T)$  was observed, in contrast to polar systems. On the other hand, in agreement with polar materials,  $E(T)$  of the microstructures was found to be the same as the constituent bulk material.

## FIGURE CAPTIONS

- Fig. 1 Measured barrier heights  $V_{B,n}$  (solid circles) and  $V_{B,p}$  (open circles) for as-grown, arsenic deposited, and arsenic-desorbed situations.
- Fig. 2 PR spectrum at room temperature from a GaAs (collector)/GaAlAs (emitter) HBT.
- Fig. 3 Calculated field profile in the collector/base region in the dark (solid lines) and under illumination (dashed lines).
- Fig. 4 Calculated field profile in the emitter/base region in the dark (solid lines) and under illumination (dashed lines).
- Fig. 5 The in-phase (open circles)/quadrature (closed circles) signals as a function of  $f_m$  for the GaAs collector signal. The solid/dashed lines are fits to a Lorentzian type function making it possible to evaluate the time constants.
- Fig. 6 The in-phase (open circles)/quadrature (closed circles) signals as a function of  $f_m$  for the GaAlAs emitter signals. The solid/dashed lines are fits to a Lorentzian type function making it possible to evaluate the time constants.

## PUBLICATIONS

### A. Invited Paper

1. Pollak, F.H., "Exciton-Optical Phonon Interaction in Reduced Dimensional Systems: Temperature Dependence of the Linewidth", in Phonons in Semiconductor Nanostructures, ed. J.-P. LeBurton, J. Pasqual and C.M. Sotomayor Torres (Kluwer, Dordrecht, 1993) p. 341.

### B. Contributed Papers

1. Yan, D., Look, E., Yin, X., Pollak, F.H. and Woodall, J.M., "Air Stabilized (001) p-type GaAs Fabricated by Molecular Beam Epitaxy with Reduced Surface State Density", Appl. Phys. Lett. 65, 186 (1994).
2. Yan, D., Pollak, F.H., Chin, T.P. and Woodall, J.M., "*In-situ* Study of Fermi Level Pinning on *n*- and *p*-type GaAs (001) Grown by Molecular Beam Epitaxy using Photorefectance", Phys. Rev. B52, 4674 (1995).
3. Krystek, W., Qiang, H., Pollak, F.H., Streit, D.C., and Wojtowicz, M., "Contactless HBT equivalent circuit analysis using the modulation frequency dependence of photorefectance", Inst. Phys. Conf. Ser. 141, 651 (1994).
4. Pollak, F.H., Krystek, W., M. Leibovitch, Qiang, H., Streit, D.C. and Wojtowicz, M., "Contactless Room Temperature Analysis of HBT Wafer Structures using Photorefectance", Proceedings of the International Workshop on Semiconductor Characterization, W.M. Bullis, D.G. Seiler and A.C. Diebold, Eds. Woodbury, NY: American Institute of Physics, 1995, pp. 669-672.
5. Yin, Y., Yan, D., Pollak, F.H., Hybertsen, M.S., Vandenberg, J.M., and Bean, J.C., "Temperature Dependence of the Fundamental Direct Transitions of Bulk Ge and Two Ge/SiGe Multiple Quantum Well Structures", Phys. Rev. B52, 8951 (1995).

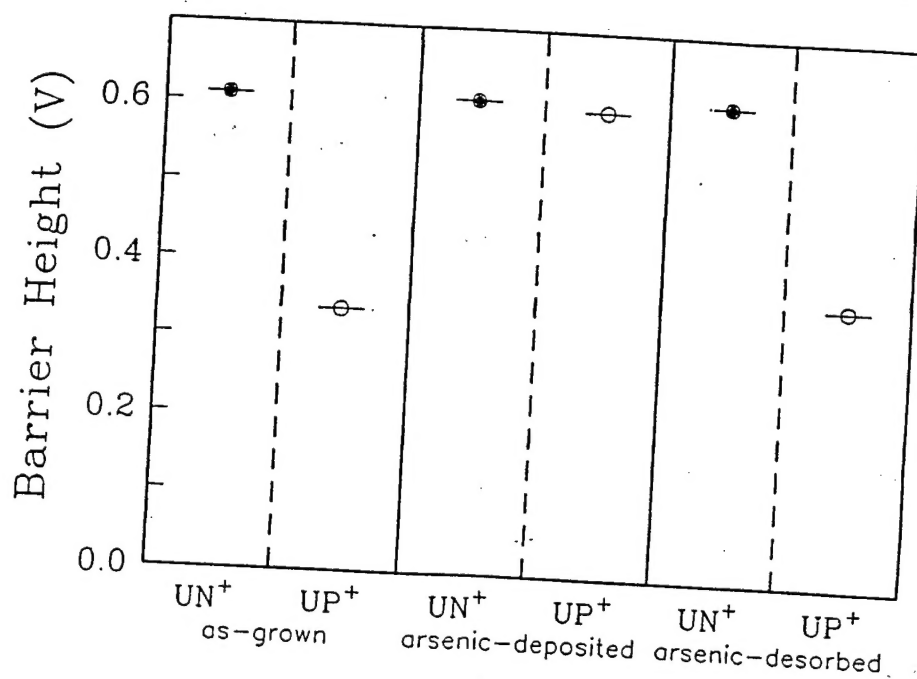


Figure 1

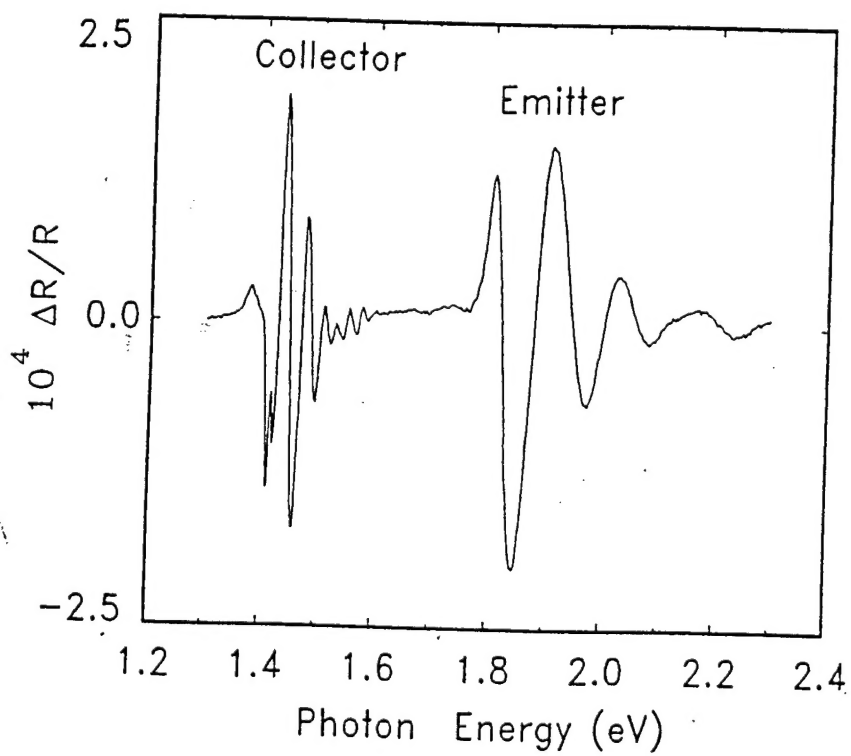


Figure 2



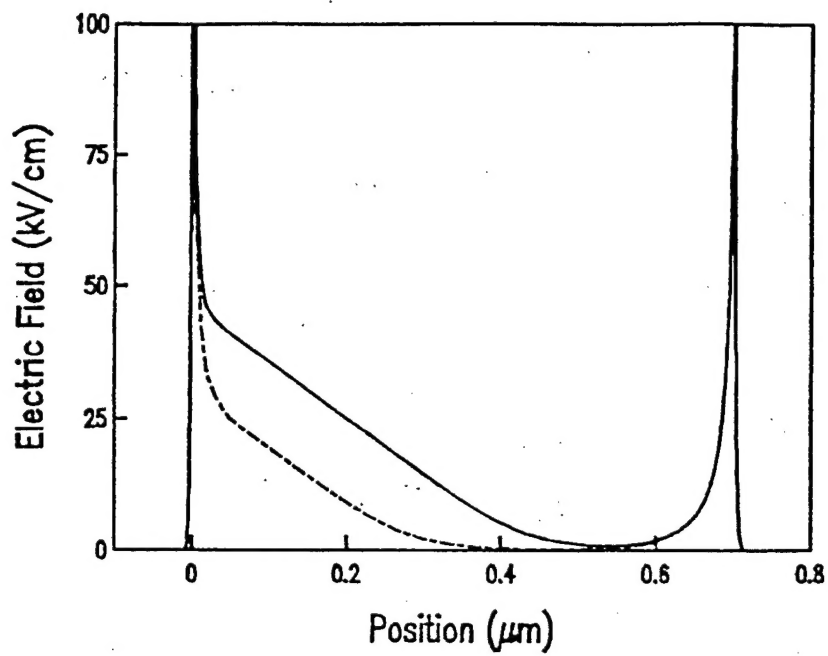


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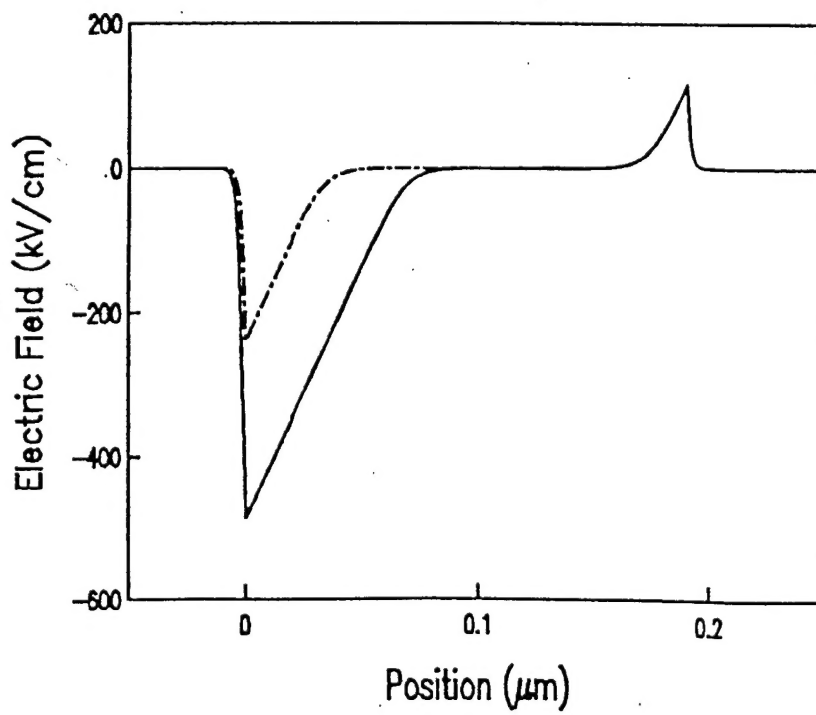


Figure 4

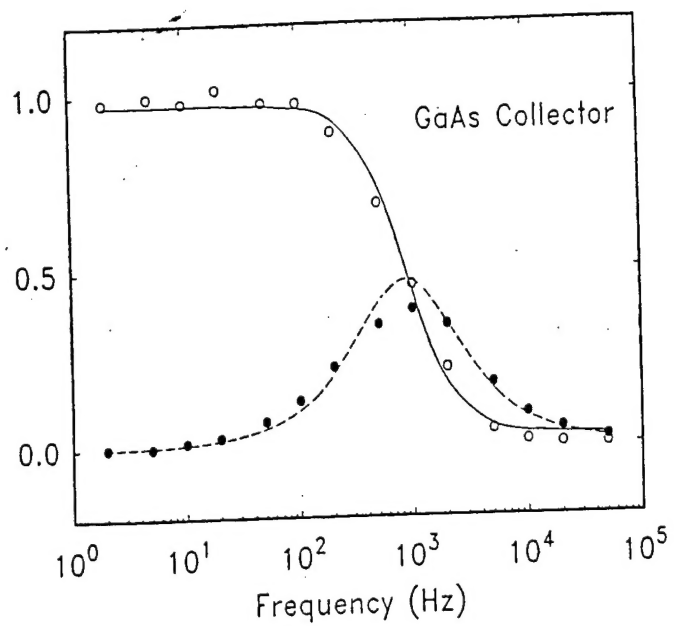


Figure 5

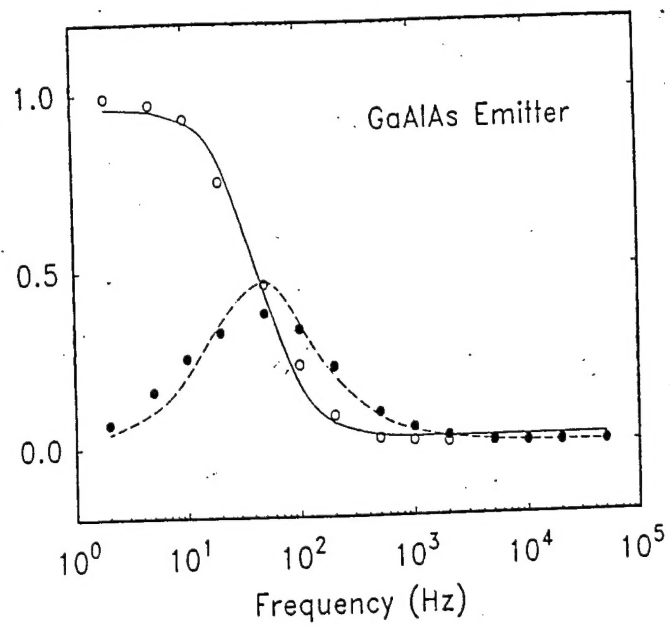


Figure 6